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Design and Performance of a Broad Range Magnetic Spectrograph

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A broad range magnetic spectrograph of Browne and Buechner type was constructed. The energy range covered by this spectrograph is from maximum to 40% of the maximum. Design, performance and an example of the momentum spectrum of reaction products obtained with this spectrograph are described.

I. INTRODUCTION

As described in the preceding paper,¹⁾ the aim of the design of the cyclotron and the beam transport system, was that the cyclotron should be used as a tool for precise nuclear physics experiment. The beam analyzer was designed to limit the energy spread below 0.1%. After the completion of the beam transport system, the next step in our laboratory was to construct a radiation detection system with high resolution. In those days of 1957, solid state detectors were still in the stage of research and development, hence the magnetic particle analyzer was the most reliable apparatus to detect particles with high resolution of energy. There were known two kinds of magnetic analyzer, *i. e.*, magnetic spectrometer and magnetic spectrograph. Magnetic spectrograph was selected because of the following reasons. First, when the spectrograph is used, one can detect simultaneously many groups of reaction product particles, thus the relative yield according to each level of the residual nucleus can be guessed and moreover, machine time for the experiment is saved to a great extent. Second, when contaminations exist in the target material, those backgrounds due to the contamination are easily discriminated by viewing the momentum spectra in a wide range.

The shortcomings of the spectrograph are such that the solid angle subtended by the spectrograph is not constant in the focal plane, and that the momentum

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resolution is different for different ion paths. To overcome these difficulties, a device was prepared to mount a detector at the position of minimum dispersion, and the spectrograph could be used as a spectrometer when the magnetic field strength is varied widely. One more difficulty, which is a special problem in our laboratory, is that the whole system of the spectrograph should be movable and be as compact as possible. This condition arose from the fact that, in our experience up to that time, the beam course of highest intensity changes when the energy of the beam is changed a little. Since we were anxious to get an intense beam, the beam transport system and also the magnetic spectrograph should all be able to change their positions according to the change of the beam course. As far as the spectrograph is concerned, this movability was achieved by constructing the spectrograph on a moving frame, just like a cannon on a platform. To prevent the frame from tilting, a counter weight of the spectrograph was mounted on the frame on opposite side of the magnet. When a change in position of the spectrograph is necessary, the magnet and the counter weight are dismantled and the frame is moved by a crane.

As reported,²⁾ the beam from the cyclotron runs horizontally at a height of 170 cm from the ground floor, then it was thought the most convenient way to handle the spectrograph is that it would have a magnetic gap to deflect particles from the target vertically downwards and the focal plane would lie near the ground floor.

In the following are reported the design principle, the construction, and the performance of a broad range magnetic spectrograph equipped in the laboratory of nuclear science.

Table I. Specifications of a Broad Range Spectrograph.

maximum to minimum energy ratio	1 : 0.3989
effective pole radius R	670 mm
range of beam radius	0.60 R to 0.95 R
maximum detectable momentum	9.0×10^5 Gauss-cm
maximum particle energy	46 MeV α and p, 23 MeV d
magnet pole gap	20 mm
magnet main coil	2784 turns. 22000 AT
magnet auxiliary coil	800 turns. 400 AT
entrance angle ϵ_1	35°
exit angle ϵ_2	0°
magnification	0.469 at 0.60 R 1.66 at 0.95 R
curvature for second order focusing	$R_1 = 443.3$ mm $R_2 = 670.0$ mm
maximum solid angle	1.451×10^{-3} sterad
focal length	163.5 mm at 0.60 R 851.8 mm at 0.95 R
minimum momentum resolution	0.05 % at 0.80 R and with source width 1 mm

II. DESIGN

The design parameters of the spectrograph are listed in Table I. The principle of broad range focusing was suggested by Bainbridge³⁾ and applied to the construction of spectrograph by Browne and Buechner.⁴⁾ This principle lies in the fact that a uniform magnetic field with a circular boundary of radius R can give one-dimensional focusing along a hyperbolic focal surface for a broad range of momenta, when the source point is placed at a distance R from the edge of the field. The larger R is the better for higher resolution, but the need to set the focal plane near the ground floor limited the maximum radius to be about 67 cm. The overall view of the spectrograph is shown in Fig. 1.⁵⁾ On the bottom lies a fixed frame and a movable platform is set on the center of the fixed frame. Spherical ball bearings are inserted between the fixed frame and the movable frame so that the movable frame can rotate horizontally free from the setting of the fixed frame. In practice, the fixed frame is adjusted to give a setting as horizontal as possible. The analyzing magnet and the counter weight are placed in opposite position on this moving platform and their weights are balanced. The error in the height of the magnet during 360° rotation is less than 0.5 mm. In the center, a reaction chamber is placed with a conical fit to the vertical axis of the fixed frame. A sliding membrane with a snout is equipped outside the chamber to serve as an inlet of the reaction particles to the analyzing magnet without breaking the vacuum.

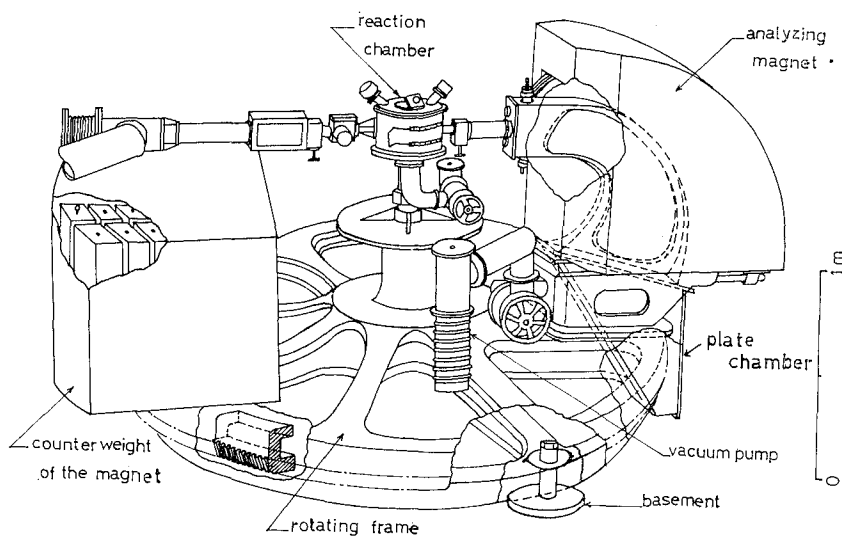


Fig. 1. Bird's-eye view of the broad range magnetic spectrograph. The analyzing magnet lies at 0° direction. (From ref. 5).

The pole shape of the analyzing magnet is shown in Fig. 2. Pole gap length is 20 mm and a vacuum duct chamber surrounds the pole tip. Both poles face directly to the vacuum. The cross section of the pole and the vacuum sealing

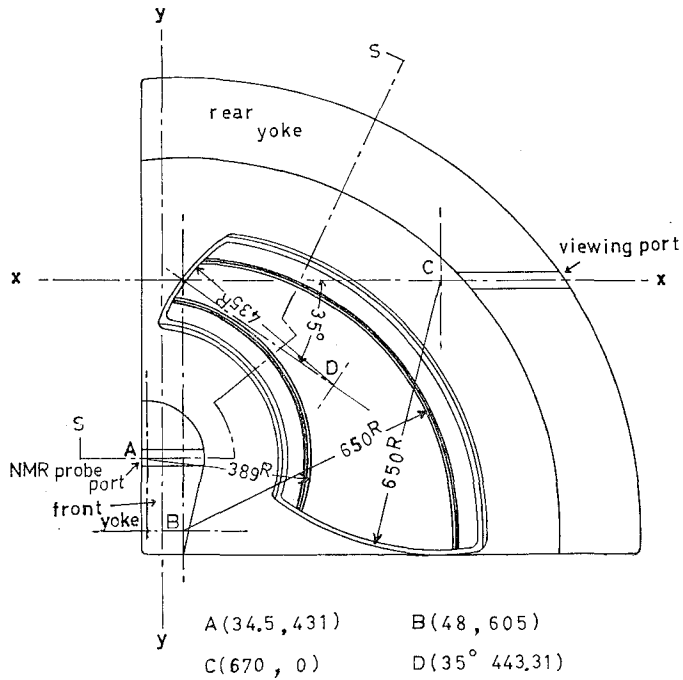


Fig. 2. Dimensions of the analyzing magnet. Symbols A, B, C and D indicate the center positions of curvature.

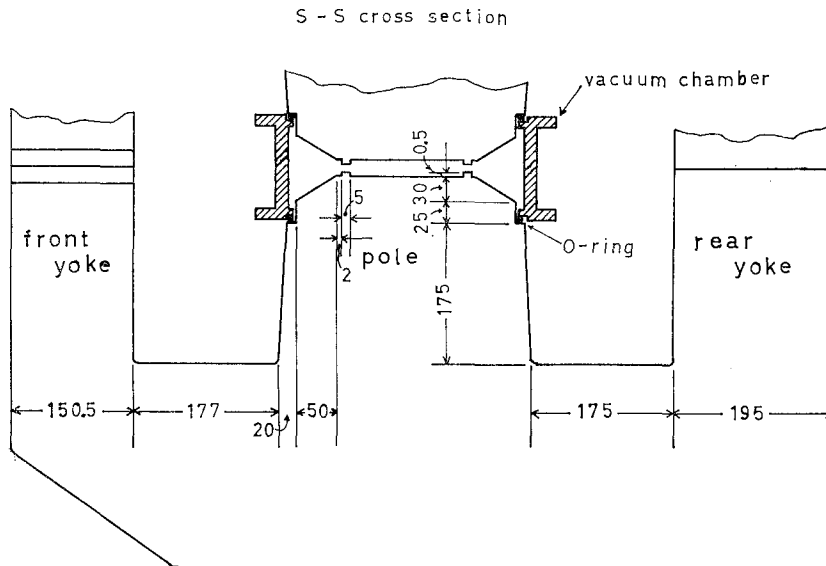


Fig. 3. Cross sections of the analyzing magnet and the vacuum chamber. Vacuum sealing mechanism is also shown.

mechanism are shown in Fig. 3. These mechanism were taken up to get a magnetic field as flat and as non-saturated as possible and to get solid angles

as wide as possible. The two faces of the poles are gold plated by chemical processing. The maximum value of the magnetic rigidity ($H\rho$) was determined to cover the most energetic protons induced by the 30 MeV alpha particles. The pole radius is 67 cm, but in practice, by taking into account the fringing field effect, the real pole radius was determined to be 65 cm to get an effective radius of 67 cm. From our experience, one gap reduction in pole radius is sufficient to get a designed range of magnetic field if the magnetic field strength is in the range of linear excitation, *i. e.*, the iron core is not saturated.

The position of the focal plane was calculated and two end points were fixed to the magnet by a jig, and emulsion plates in a holder were forced to take the curve of focal plane by pressing the emulsion plate to a backing plate machined to the profile of the focal plane. The emulsion plate holder could mount two sets of plates and could be rotated with a geared motor, therefore two exposures can be taken without breaking the vacuum. For a 90° or a 270° rotation of the holder, the two sets of plates lie parallel to the beam and the beam can pass through a gap between the plates.

The beam duct of the spectrograph was separated into three parts; entrance channel, inside the magnet channel and outside the magnet channel. The entrance part was equipped with a snout, slit system and a vacuum valve. The middle part had two holes fitted to the magnet pole. Third part, the outside part, was equipped with a hole to mount a scintillation counter for the detection of particles and for the use of the spectrograph as a spectrometer. The emulsion plate holder is free from the duct. To prevent the pole gap from non-uniform distribution, spacers made of non-magnetic stainless steel were prepared but because the bending of the magnet caused by the magnetization was calculated to be negligible, and because momentum spectra of reaction particles obtained with no spacers were satisfactory, no spacers are used until now.

As pointed out by Ewald and Hintenberger,⁶⁾ the effect of the fringing field could be diminished by the use of a magnetic channel. Eleven kinds of magnetic channels were prepared to correct the fringing field of the entrance side of the analyzing magnet. Each channel has different thickness and if attached to the magnet, the boundary of the magnet changes its shape and the cut-back of the pole boundary described above can be corrected. However, until now, the use of these magnetic channels were not tried and we have no experience about the effect of these channels or about the sharp cut-off of the magnetic field. Hence the figure and detailed explanation of the magnetic channel are omitted.

The shape of the reaction chamber can be seen from Fig. 1. The mechanism of this chamber is so complicated that the figure of which is omitted. The reaction chamber is equipped with a collimator, target holder, Faraday cup and two open windows. The windows are vacuum sealed by moving membranes and the membrane is connected to the vacuum duct of the magnet. Windows are opened at forward and backward angle separately and the particles emitted from the target could be detected from -10° to $+80^\circ$ and -70° to -150° . Minus sign means the angle is in the third or fourth quadrants with respect to the beam direction. The Faraday cup is removed downwards automatically when the

snout of the duct goes from plus side of the beam to the minus side of the beam.

Figure 4 shows the schematic diagram of the main coil excitation power source. In the initial stage of the system design, a motor-generator coupled with a d. c. amplifier system was supposed as a power source of the magnet, but the noise from the motor-generator was a source of troubles from our experience, so a power source of vacuum tube was designed in place of a motor-generator. Furthermore, to obtain a magnetic field of stability less than 0.01%, an auxiliary coil was prepared and the exciting current of the auxiliary coil was regulated by a signal from the nuclear magnetic resonance in the magnetic field of the spectrograph magnet. The block diagram of the main coil excitation system and of the field regulation system are shown in Figs. 4 and 5 respectively.

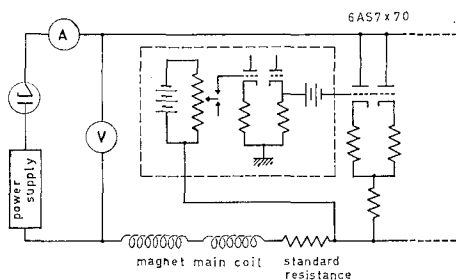


Fig. 4. Block diagram of the power supply for the main exciting coil of the analyzing magnet.

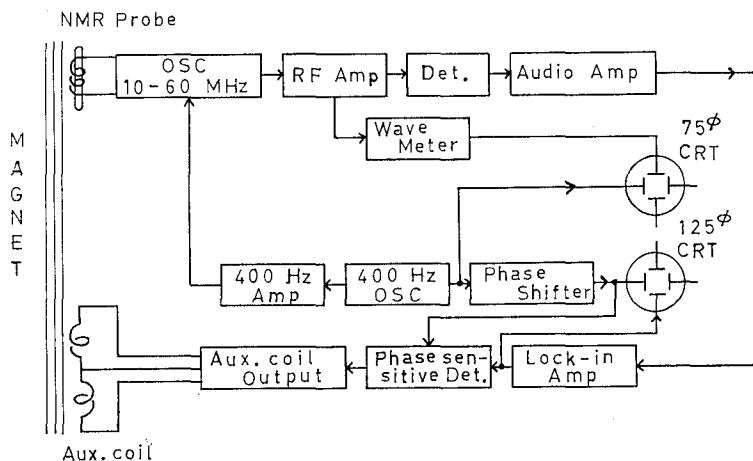


Fig. 5. Block diagram of the field stabilizing system.

III. PERFORMANCE

The excitation of the magnet were measured with the NMR method and the result is shown in Fig. 6. In this figure, the experimental points fluctuate a

Broad Range Spectrograph

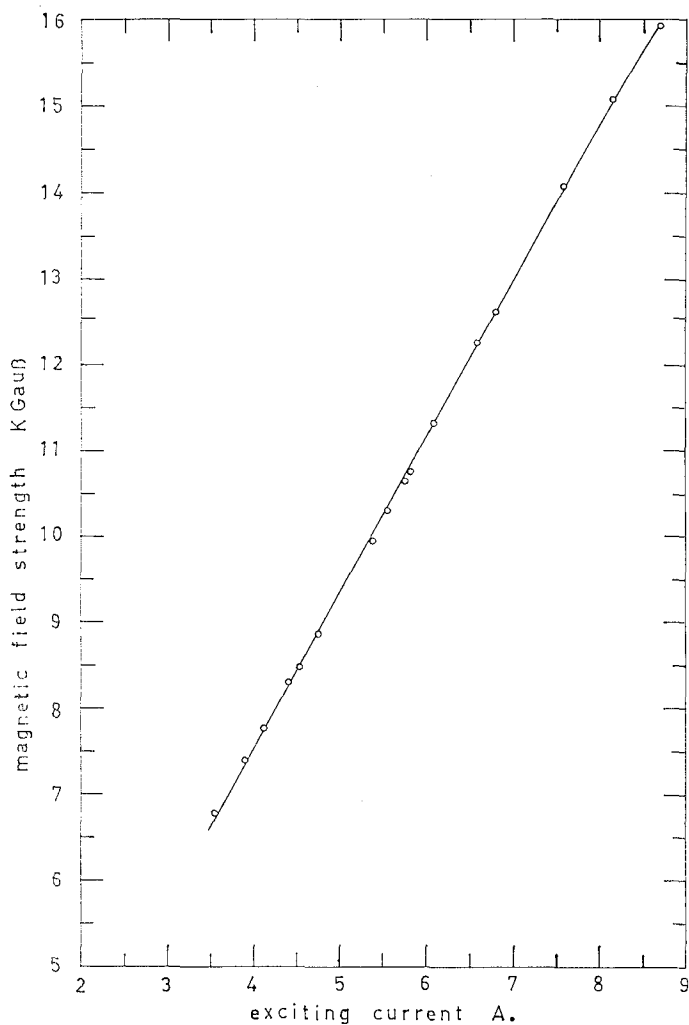


Fig. 6. Excitation curve of the analyzing magnet. Open circles are the points of measured values with an NMR method. Small fluctuations of experimental points are due to the hysteresis of the magnet.

little, but this fluctuation is due to the hysteresis of the magnet. The excitation is linear up to about 15 K Gauss and this spectrograph can reach higher values of magnetic rigidity than the designed value if the exciting current is increased. The magnetic field is constant over several hours.

The location of the focal plane was tested roughly in the following manner. Proton beam from the cyclotron was deflected by the beam analyzing magnet and then brought into the reaction chamber. At the center of the chamber, a gold foil of 0.2 mg/cm^2 thick was mounted and the beam was scattered by this target. At the entrance of the broad range spectrograph three sets of slit system were prepared. At the position of the emulsion plate, glass plate covered with scintillation phosphor material was placed. The front panel of the emulsion plate chamber was replaced with an epoxy-glass instead of metal plate and the

scintillation spot at the phosphor was observed from outside. The spectrograph was set at 0° and the beam scattered by the target entered the spectrograph. In the first stage of the experiment, the beam was divided by the slit system into three courses, one goes through the upper slit and enters the magnet at 15 mm high from the center line, another beam goes through the middle slit and along the center line and the third beam goes through the lower slit at 15 mm from the center line. The bright spot on the phosphor plate produced by each beam was observed and was surveyed if the spot changes its position according to the difference of the beam course. The coincidence of the position was confirmed at several strength of the magnetic field so that the luminescence point was transferred to several positions in the focal plane. It was observed that, when the target was placed at the center of the reaction chamber, beams of three different courses emerged into the same point and then the source point-focal plane relation was satisfied in a crude approximation.

In the second stage of the experiment, the gold foil target was removed towards the collimator of the reaction chamber by an amount of 60 mm. Observations of the beam spot on the fluorescence screen were carried out in the same manner as described above. It was confirmed that three trajectories of the beam did not coincide at the same point of fluorescence screen and the source point of the spectrograph did not lie 60 mm apart from the center. Further, the spread of the beam on the focal plane indicates the out-of focusing image width and the width could be calculated if assumed that the source point lies exactly at the center of the reaction chamber. From the comparison between the calculated width and the observed width, it was concluded that the source point lay at the center of the reaction chamber within the error of few mm.⁷⁾

The relation between the momentum of the incoming particle and the distance along the focal plane was calibrated by the use of standard source of ThC and ThC'. Alpha particles of 6.0466 MeV and 6.0861 MeV from ThC and of 8.7801 MeV from ThC' were brought to focus by the spectrograph. The source width was 1.09 mm and the solid angle subtended by the spectrograph was limited to 0.0324 radian. Emulsion plates were set at the focal plane and the magnetic field of the spectrograph was varied in several steps. The relation obtained is expressed,

$$\begin{aligned} \frac{r}{R} = & 0.96004 - 2.6969 \times 10^{-4} l \\ & - 1.25382 \times 10^{-7} l^2 \\ & - 4.85631 \times 10^{-11} l^3 \end{aligned}$$

where r is the radius of curvature of the particle, R the radius of the pole (670 mm) and l the distance along plate. Figure 7 shows the above relation graphically. Momentum of the particle can be estimated on the basis of this relation when the distance along plate and the magnetic field strength are known. Wide carriage microscope was constructed to scan the emulsion plate of the spectrograph.

Broad Range Spectrograph

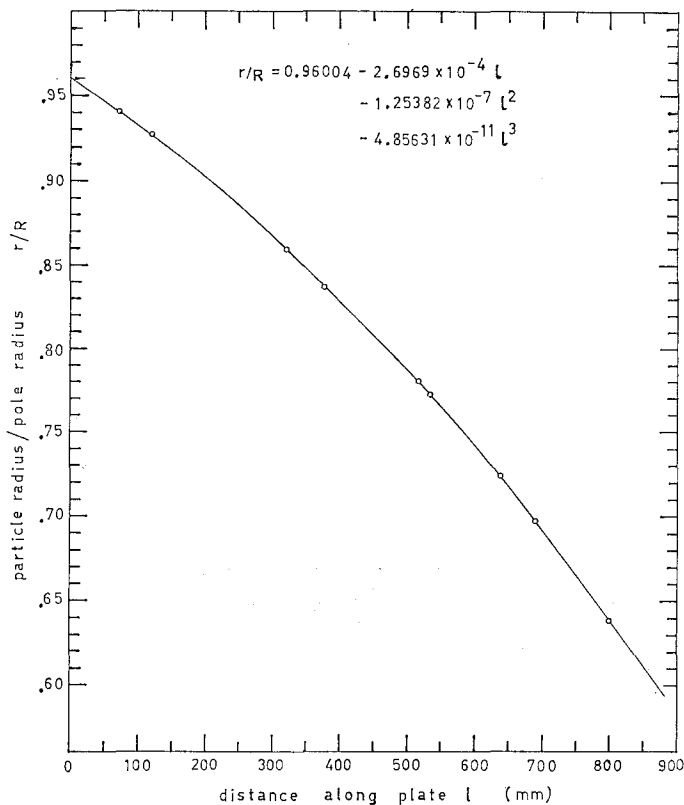


Fig. 7. Relation between the particle momentum and the distance along plate. The momentum is expressed in terms of r/R , where r is the radius of curvature of the particle and R is the pole radius.

The resolution of the spectrograph could be determined by observing the widths of alpha particle tracks on the emulsion plate. Figure 8 shows the energy resolution obtained experimentally and that calculated for the source

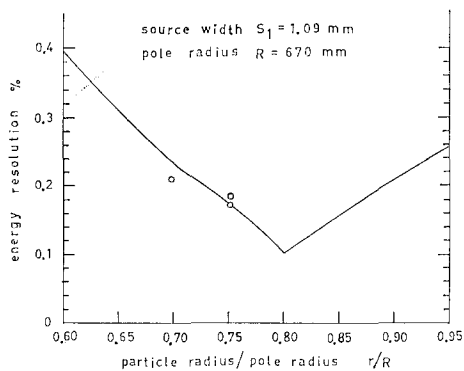


Fig. 8. Energy resolution as a function of particle momentum. Second order focusing is achieved at $r/R=0.80$. Open circles indicate the resolution obtained experimentally with the standard alpha particles from ThC' .

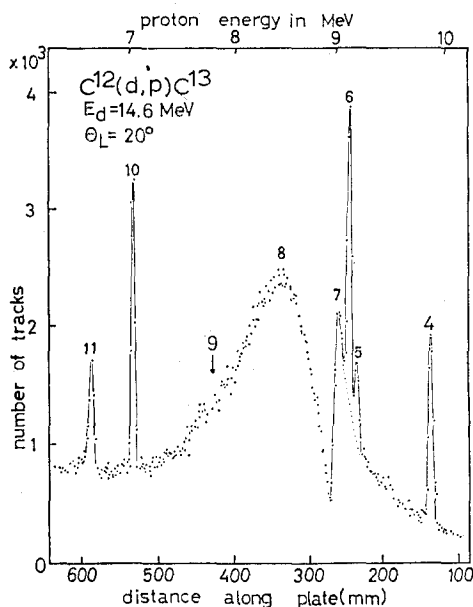


Fig. 9. Momentum spectrum of protons from the reaction $C^{12}(d,p)C^{13}$.
From ref. 7).

width of 1.09 mm. The calculated curve is in good agreement with the experimental results. The resolution is, as seen from Fig. 8, not determined in the whole range of the focal plane, but the experiment of nuclear reactions using this spectrograph confirmed that the resolution is in good agreement with the predicted curve on the whole range. Figure 9 shows the momentum spectrum of protons⁸⁾ from the reaction $C^{12}(d,p)C^{13}$. Figures in Fig. 9 indicate the proton groups leading to the excited states of C^{13} . 7.47 MeV state (5) and 7.53 MeV state (6) of C^{13} are clearly separated from each other. Broad peak signed as 8 in Fig. 9 shows the proton group emitted from the neutron decaying state of C^{13} . This peak is the result of final three body (d, p) stripping ($C^{12}+d \rightarrow n+p+C^{12}$). If the resolution of the detection system is not good, this peak could not be observed because the peak is smeared out and is mistaken for a meaningless background.

IV. CONCLUSION

The broad range magnetic spectrograph have been used in nuclear physics research since 1963.⁹⁾ The works done with this spectrograph cover not only the nuclear reactions leading to the definite energy levels of the residual nuclei but also the determination of the energy loss of charged particles in matter with high precision. Other feasibilities could be found and this apparatus would prove to be very efficient tool for the nuclear physics research. At present, from our experience, some inconveniences are found in the stabilization system of the magnetic field and in the time-consuming method of the emulsion plate scanning. These factors will be improved by replacing the power supply of the

Broad Range Spectrograph

magnet with other devices, for example an SCR system and replacing the emulsion plate by an array of solid state detectors, or a solid state position counter.

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